

## Tillage system effects on runoff and sediment yield in hillslope agriculture

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### Abstract

Runoff and soil erosion are major factors of land and lake degradation in the Patzcuaro Watershed located in Michoacan, Mexico. This non-point source pollution results from corn cultivation on steep cropland sites. In the local farming system, the soil is bare for much of the year and subject to frequent plowing and cultivation. Conservation tillage and the use of crop residues for soil protection have only recently been introduced in this region. Runoff plots (25 m × 4 m) were used to collect runoff ( $Q$ ) and sediment yield ( $Sy$ ) data to identify a tillage system that allows soil restoration. The groundwater loading effects of agricultural management systems (GLEAMS) model was calibrated using runoff and sediment information from four tillage treatments that evaluated soil erosion and estimate the long-term sustainability of current and alternative farming systems. Four runoff plots planted with rainfed corn were used for these treatments: (1) conventional tillage (CT), (2) no-tillage without residue cover (NT-0), (3) no-tillage with 33% residue cover (NT-33), and (4) no-tillage with 100% residue cover (NT-100). The results indicated that CT and NT-0 treatments produced higher  $Q$  and  $Sy$  than those having residue cover. Simulated  $Sy$  of NT treatments was much better than simulated  $Sy$  of CT, based on their agreement with observed  $Sy$ . These results are relevant to recommend no-till agriculture as Best Management Practice for agricultural land requiring restoration activities. © 2001 Elsevier Science B.V. All rights reserved.

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### 1. Introduction

Mexico's national territory comprises 331 major watersheds, of which 11 are severely polluted, 218 seriously contaminated and the rest exhibit some degree of deterioration. A continuous process of

vegetation cover reduction has induced soil erosion and nutrient losses in most watersheds with the consequent eutrophication of water bodies. Deforestation activities, to incorporate new land for crops, are the major anthropogenic causes of land degradation with a strong impact on natural resources. After 1960, Mexico has reduced its temperate and tropical forests by 30 and 75%, respectively. Today, Mexico ranks third among countries with the highest annual

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rates of deforestation (World Resources Institute, 1994).

The state of Michoacan, in Central Mexico, has not been excluded from natural resources degradation. Pressure to convert forests to croplands has resulted in an extensive agricultural development over the rich soils of the Mexican Neo-Volcanic Central Belt. Consequently, many lakes are being affected by eutrophication due to upland water erosion and nutrient runoff, such as the Patzcuaro Lake in the Patzcuaro Watershed (Toledo et al., 1992) where agriculture is practiced on steep terrain. O'Hara et al. (1993), indicated that at least 40% of sediment eroded from the slopes reaches the lake.

Agricultural uplands are very susceptible to soil water erosion when repeatedly tilled and left without a protective cover. The rate of soil water erosion on steep croplands increases as the square of the slope (Lal, 1995) and transported sediment particles provoke severe off-site damage to water systems (Pimentel et al., 1997). An effective management practice to alleviate agricultural contributions to non-point source pollutants is protection of the soil surface from the erosive forces of rainfall (Renard and Mausbach, 1990; Park et al., 1995; King et al., 1995). Rainfall interception, by crop canopy and residue cover, reduces soil particle detachment by raindrop impact and sediment transported by concentrated overland flow (Bingner et al., 1992), which along with a reduction of mechanical soil movement, constitute the basis of conservation tillage (Lal, 1995).

Sustainable agricultural systems that reduce soil erosion need to be identified. Simulation models that evaluate the effects of management practices on environment, runoff, erosion and productivity (Lane et al., 1992), provide a sound framework for identifying significant trends and changes, and contribute to the development of appropriate intervention or alternative management strategies (White et al., 1993). The challenge is to decide on a strategy to develop and implement support technology for water quality decision-making (Stone et al., 1993).

Few long-term data sets of runoff, watershed scale are available in Mexico and Central America. The cost of acquiring such data is frequently too high to justify long-term monitoring. Decisions on natural resource management are urgently needed and cannot wait for complete data sets. One strategy is to use short-term

plot data to parameterise simulation models then use these models and long-term observed or simulated climatic data to project the effects of management systems on key components of the natural resource system.

A set of runoff plots was established to evaluate the effects of traditional and conservation tillage on runoff volume and sediment yield at Ajuno, near Patzcuaro, Michoacan in Central Mexico. Experimental objectives were to quantify the effects of conservation tillage on runoff and sediment yields and to parameterize the GLEAMS model developed by Leonard et al. (1987), and later used it with additional climatic data to project the effects of conservation tillage systems on long-term runoff and sediment yield.

## 2. GLEAMS' governing equations

The groundwater loading and evaluation of agricultural management systems (GLEAMS) model is a process-based continuous simulation set of steady-state equations using basic hydrological variables and consequent soil erosion on a storm basis. The hydrological model component that calculates the infiltration-runoff process is based on the "curve number" approach developed by the Natural Resource Conservation Service (NRCS) according to the following expression:

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \quad (1)$$

where  $Q$  is the storm runoff volume (cm),  $P$  the precipitation (cm) and  $S$  the available soil water storage or retention (cm) on the day that precipitation occurs. GLEAMS relates the retention parameter  $S$ , to the soil water content as

$$S = S_{mx} \frac{UL - SM}{UL} \quad (2)$$

where  $SM$  is the current soil moisture in the root zone (cm) and  $UL$  the upper limit of soil water storage in the root zone (cm) and  $S_{mx}$  the maximum value of  $S$  estimated for soil moisture condition 1 (dry,  $CN_1$ ) used in the NRCS equation:

$$S_{mx} = 2.54 \left( \frac{100}{CN_1} - 1 \right) \quad (3)$$

where  $CN_I$  is the curve number for soil moisture condition I calculated from the  $CN_{II}$  (obtained for any hydrologic soil and land use treatment) with the polynomial equation:

$$CN_I = 1.348(CN_{II}) - 0.01379(CN_{II})^2 + 0.000118(CN_{II})^3 - 16.91 \quad (4)$$

The erosion model component of GLEAMS estimates soil erosion using the plane concept, and assumes that sediment load is limited by either the amount of sediment available for detachment or by the transport capacity of the flow (Foster et al., 1980). Computation of sediment movement down slope obeys a continuity mass expression with the following terms:

$$\frac{dq_s}{dx} = D_L + D_F \quad (5)$$

where  $q_s$  is the sediment load ( $\text{kg m}^{-1} \text{s}^{-1}$ ) at the  $x$  point distance down slope (m),  $D_L$  the lateral inflow of sediment ( $\text{kg m}^{-2} \text{s}^{-1}$ ),  $D_F$  the detachment or deposited sediment by the flow ( $\text{kg m}^{-2} \text{s}^{-1}$ ). Because a first attempt in this research was to estimate sediment yield at runoff plot scale, only overland flow element was

quantified, the basic erosion relationships are:

$$D_L = 0.21 EI(s + 0.014)KCP \left( \frac{\Phi_p}{V_u} \right) \quad (6)$$

$$D_F = 37983 m V_u \Phi_p^{1/3} \left( \frac{x}{72.6} \right)^{m-1} s^2 KCP \left( \frac{\Phi_p}{V_u} \right) \quad (7)$$

where  $EI$  is the Wisheimer's rainfall erosivity factor ( $\text{MJ mm ha}^{-1} \text{h}^{-1}$ ),  $s$  the sine of slope angle,  $K$  the USLE soil erodibility factor ( $\text{Mg ha h ha}^{-1} \text{MJ}^{-1} \text{mm}^{-1}$ ),  $C$  the soil loss ratio (SLR) of the USLE cover management factor (dimensionless),  $P$  the USLE contouring factor (dimensionless),  $\Phi_p$  the peak runoff rate ( $\text{mm h}^{-1}$ ),  $V_u$  the storm runoff volume (mm) estimated from Eq. (1),  $m$  the exponent in the slope-length factor, and  $x$  the distance down slope (m).

### 3. Materials and methods

A set of USLE-type runoff plots were established to evaluate four tillage treatments in terms of storm runoff volume and sediment yield at Ajuno, an experimental site near Patzcuaro, Michoacán in Central

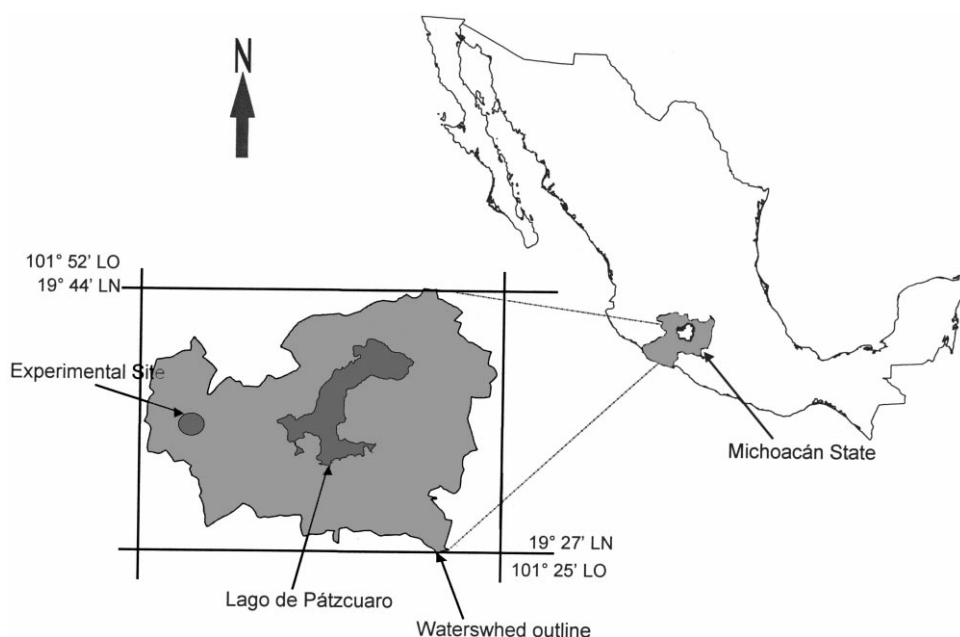


Fig. 1. Geographic location of the Patzcuaro watershed in Central Mexico.

Mexico (Fig. 1) belonging to the National Sustainable Production Center (CENAPROS-INIFAP).

The experimental site, is representative of thousands of small farms in Mexico, each practicing slope agriculture in Andisols under a temperate sub-humid climate. Andisols in this region are derived from volcanic ash, are more than 4 m in depth, have a sandy loam texture, and a very low bulk density ( $<1.0 \text{ g cm}^{-3}$ ). They are poorly structured, easily erodible under dry or wet conditions (Cabrera, 1988) and are slightly acid in pH. The site is 2200 m above sea level, with an annual mean temperature of  $16^\circ\text{C}$  and 1002 mm of average annual precipitation.

### 3.1. Treatments

Four runoff plots, 25 m long by 4 m wide at 9% of slope, were constructed. Tillage treatments used were: (1) conventional tillage (CT), (2) no-tillage with 0% of residue soil cover (NT-0), (3) no-tillage with 33% residue cover (NT-33), and (4) no-tillage with 100% residue cover. CT involved a plow-type soil movement, row building and two cultivations in the ridges. CT is the prevalent local farming system, occurring on perhaps 40% of the total watershed area, while NT is a soil management practice not yet used in the watershed. The rest of the watershed area is forest and urban use. Chopped maize residue was applied to provide 33 and 100% soil coverage over the runoff plot as measured with a pin-type soil cover meter.

During the last week of June 1996 and third week of May 1997, rainfed maize of a local variety was sown to establish the CT and NT treatments. Each runoff

plot was planted at 40,000 plants  $\text{ha}^{-1}$  and fertilized with 60–60–00 kg NPK  $\text{ha}^{-1}$ . Another 60 kg N  $\text{ha}^{-1}$  were applied 30 days after planting. Soil samples were analyzed to obtain the physical and chemical characteristics of the soils required by GLEAMS. Plots fulfilled the stipulations of homogeneous soil, single crop at any time, single management practice and uniform rainfall over the entire area (Knisel and Williams, 1995). Total daily rainfall, storm intensity, air temperature, solar radiation, weekly leaf area index and crop cover were measured throughout the rainfall season (May–October). Sediment concentration in 1-l aliquots of water runoff, were used to calculate storm erosion from rainfall excess. When total water exceeded 50 l, a collector tank at the bottom of the plot diverted one eighth of water excess to a second collector tank.

### 3.2. Model inputs

The GLEAMS hydrological component requires climate, soil and crop management input variables to simulate the hydrological behavior of the actual system. Observed daily maximum and minimum air temperatures, and total 24 h precipitation from year 1996 constituted the climatic input data. The sandy loam texture characteristics of runoff plots soil in was utilized to compute the USLE soil erodibility  $K$  factor:  $0.038 \text{ t ha h mm}^{-1} \text{ MJ}^{-1} \text{ ha}^{-1}$ . The erosion component does not require calibration, but it required the SLR adjusted to crop canopy cover changes during the growing season (Davies et al., 1990). Table 1 presents the major input model parameters needed for model calibration.

Table 1  
Soil input parameters required by GLEAMS and obtained at Ajuno Experimental Station

Input parameter	NT-0	NT-33	NT-100	CT
Field capacity, $-0.33 \text{ bar (mm mm}^{-1}\text{)}$	0.11	0.12	0.12	0.13
Wilting point, $-15 \text{ bar (mm mm}^{-1}\text{)}$	0.06	0.07	0.07	0.07
Organic matter (%)	1.67	1.51	2.11	2.10
Bulk density ( $\text{g cm}^{-3}$ )	0.98	0.97	0.99	0.99
Manning $n$ surface ( $\text{s m}^{-3}$ )	0.02	0.04	0.07	0.02
CN	93	87	87	93
SRL				
Initial	0.95	0.26	0.20	0.85
Mid-season	0.55	0.12	0.08	0.43
Final	0.08	0.03	0.02	0.07

### 3.3. Model calibration and validation

For each rainfall event a curve number value was obtained by solving for  $S$  using Eq. (1) as suggested by Ponce and Hawkins (1996). For a given  $P$  and  $Q$  paired observation, an  $S$  value was calculated and the corresponding CN was computed:

$$S = 5[P + 2Q - (4Q^2 + 5PQ)^{1/2}] \quad (8)$$

To calibrate the hydrologic component of the GLEAMS model, the average curve number was varied until a minimum difference between the actual and simulated runoff was reached according to the following objective function:

$$D_{\min} = \sum_{i=1}^m (Q_{om} - Q_{sm})^2 \quad (9)$$

where  $Q_{om}$  and  $Q_{sm}$  are the observed (o) and simulated (s) runoff ( $Q$ ) of the month ( $m$ ). The value of CN with the minimum square difference ( $D_{\min}$ ) was selected to perform the model simulations. To evaluate the model's accuracy, observed and estimated data was subjected to regression analysis and to a model efficiency index ( $E$ ) developed by Nash and Sutcliffe (1970):

$$E = \frac{\sum_{i=1}^n (x_i - m)^2 - \sum_{i=1}^n (x_i - e_i)^2}{\sum_{i=1}^n (x_i - m)^2} \quad (10)$$

where  $X_i$  is the observed runoff or sediment yield of the  $i$ th month,  $m$  the observed average and  $e_i$  the estimated monthly runoff or sediment yield.  $E$  values over 0 indicate the efficacy of the model over the average of observed runoff or sediment yield. A value of 1 indicates a perfect model fit.

### 3.4. Model prediction

After GLEAMS model calibration, long-term simulations were performed for a range of slope steepness (3–25%) and using an 18-year climatic data set. The slope range comprises actual watershed agricultural hillslopes. Sediment yield ( $Sy$ ) was simulated in the four treatments since soil erosion is the main source of pollution for the lake. The evaluation factor was surface slope because hillslope agriculture is practiced in a wide range of slopes in the Patzcuaro watershed while other environmental characteristics are almost constant. Sediment yield outputs were fitted through regression analyses.

## 4. Results and discussion

### 4.1. Observed hydrology

A primary goal for model application in the Patzcuaro watershed was to understand the hydrological behavior of tillage systems under local hillslope and climatic conditions. During data collection, from May to October, 1996, 72 rainfall events were observed at the experimental site with 692 mm of accumulated precipitation. The mean depth of rainfall event was 13.6 mm, the maximum 24 h precipitation was 54.1 mm, and the maximum 30 min intensity was 34 mm h<sup>-1</sup>. Rainfall kinetic energy varied as a function of rainfall depth and storm intensity. From 2361 EI<sub>30</sub> units accumulated, 24% of the events (large to mid-size storms) contributed 1683 EI<sub>30</sub> units, while 47% of the events (small storms) produced only 216 EI<sub>30</sub> units. Most rainfall erosive force resulted from very few storm events, which caused significant soil loss in cropland fields especially in those without protective cover (Fig. 2).

Observed rainfall kinetic energy expressed in EI<sub>30</sub> terms with units MJ mm ha<sup>-1</sup> h<sup>-1</sup> was within the range of the Erosion Index for this region according to isoerodent maps developed by Figueroa et al. (1991). Villar (1996) established an Erosion Index of 5000 MJ mm ha<sup>-1</sup> h<sup>-1</sup> in the humid tropical region of Chiapas, where fields with 20% slope are often used for cropland agriculture.

Runoff volume and sediment transported off the plots diminished as ground cover increased and soil tillage decreased. Highest runoff and sediment yields were observed for the NT-0 and CT treatments while lowest values occurred in the no till system having any amount of residue cover (NT-33 and NT-100).

Water infiltration (total rainfall minus total runoff) increased 10.9% with residue cover augmentation and no-tillage, 606.8 mm on CT to 672.8 mm on NT-100. Total runoff volume was highest for NT-0 with 91.5 mm and lowest for NT-100 with 19.6 mm, while CT produced 86.6 mm of runoff. The runoff–precipitation ratio was 0.124 for CT and 0.028 for NT-100. Oropeza et al. (1995), in nearby Andisols under CT, reported runoff–precipitation ratios from 0.32 to 0.62. Variations in the runoff–precipitation ratios can be attributed to inter-annual kinetic energy variability from occurring storms.

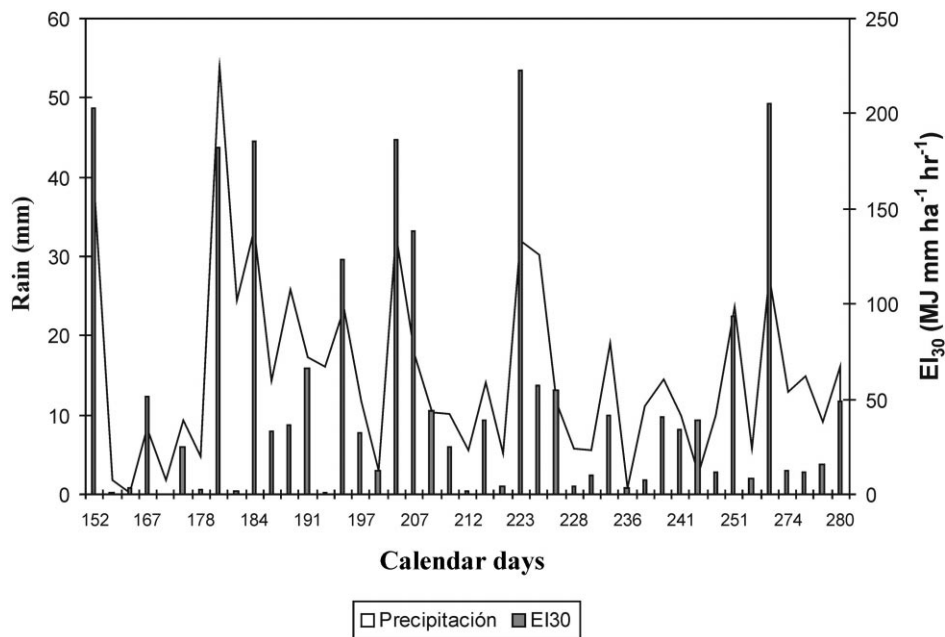


Fig. 2. Rainfall and  $EI_{30}$  registered in the studied period at Ajuno, Michoacan.

Sediment yield (Sy) reduction for the no-till system resulted from a reduced transport capacity of overland flow due to the low flow velocity imposed by the cornstubs over the ground (Fig. 4). Sediment yield differences between tillage treatments are highly significant. Sy from NT-100 was  $0.3 \text{ Mg ha}^{-1}$  while the local CT system produced soil losses of  $2.5 \text{ Mg ha}^{-1}$  in 1996. O'Hara et al. (1993) estimated that prehispanic agriculture in the region produced around  $0.36 \text{ Mg ha}^{-1} \text{ yr}^{-1}$  of eroded soil. Today soil losses above  $10 \text{ Mg ha}^{-1}$  are commonly observed. Since all overland flow from the uplands collects in a single

lake having no outlet, sedimentation of the Patzcuaro Lake is occurring.

#### 4.2. Simulated runoff

Proficiency of the GLEAMS model in predicting monthly and total seasonal runoff volume and sediment yield on hillslope fields was analyzed. Fig. 3 shows observed and predicted monthly runoff volume. Based on the determination coefficient ( $r^2$ ), simulated and observed runoff were linearly related ( $r^2$  was above 0.67 for all the treatments, Table 2). Monthly

Table 2

Total seasonal observed (o) and simulated (s) runoff volume and sediment yield, determination coefficients and model efficiency index ( $E$ ) for tillage treatments

Tillage treatment	Total runoff (mm)				Total sediment yield ( $\text{Mg ha}^{-1}$ )			
	o	s	$r^{2a}$	$E^a$	o	s	$r^2$	$E$
CT	85.7	86.1	0.99	0.67	3.2	3.8	0.98	0.95
NT-0	91.4	84.1	0.95	0.80	3.6	4.3	0.97	0.96
NT-33	23.7	20.1	0.89	0.70	0.8	0.8	0.98	0.96
NT-100	20.9	20.6	0.99	0.97	0.3	0.3	0.95	0.95

<sup>a</sup> Calculated from monthly values.

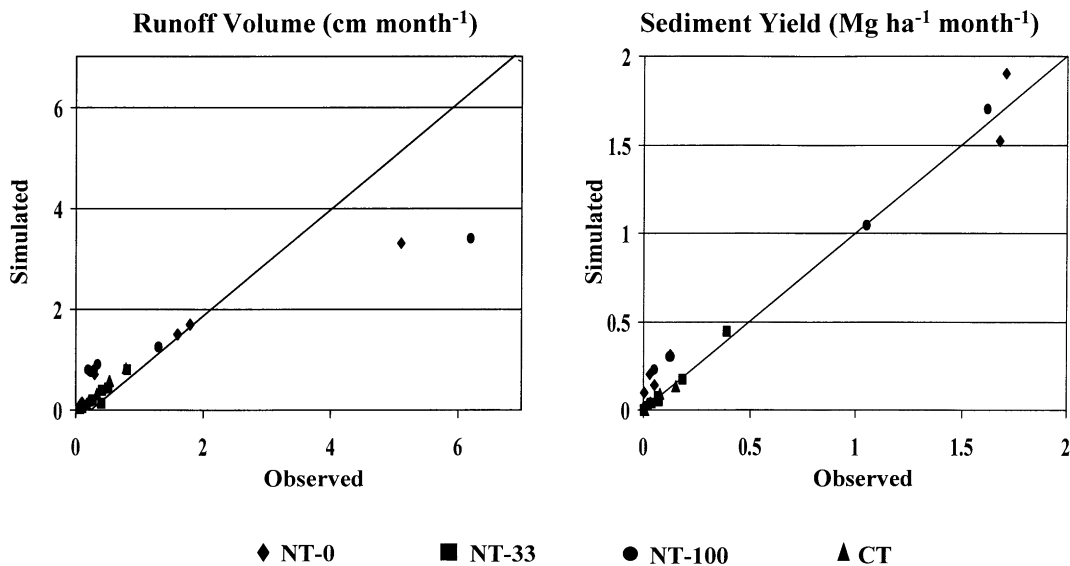


Fig. 3. Simulated and observed monthly runoff volume and sediment yield for tillage treatments.

runoff volume estimates for NT-0 and NT-100 were over-predicted for large runoff events, but acceptable for mid-size and small runoff events. The  $E$  coefficients were higher for NT treatments than for CT (Table 2). This indicates a good model performance in predicting the monthly runoff volume on mulched and no-tilled fields.

The lower ability of the model to predict monthly runoff volume for the CT plot can be attributed to the use of a single CN value for the entire growing season. It must be remembered that the CN parameter was computed with model calibration. We have found changes in CN on the CT system due to crop growth and surface roughness modifications with soil cultivation. Modifications of surface roughness in CT fields subjected to furrow cultivation commonly affect runoff volume estimates by models.

Differences between observed and simulated runoff were small when total seasonal amounts are considered. Seasonal runoff predictions of GLEAMS are significantly better than monthly runoff predictions because of the unique CN value for the entire season.

#### 4.3. Simulated sediment yield

GLEAMS efficiency in estimating sediment yield from the four treatments was acceptable considering the  $E$  index (Table 2). Some difficulties were detected

in simulating Sy for the NT-0 due to inaccuracies in runoff estimate. Note that runoff volume is obtained with Eq. (1) and later required to estimate the lateral sediment contribution ( $D_L$ ) using Eq. (6) as well as and the detached and deposited sediment by the flow ( $D_F$ ) using Eq. (7). This indicates that sediment yield predictions by GLEAMS are very sensitive to  $Q$  via CN calculation.

In general, the GLEAMS model performance was better in predicting total seasonal Sy than  $Q$ . Model efficiency ( $E$ ) and  $r^2$  coefficient were higher in Sy estimation than those found in  $Q$  estimation. This was pointed out by Villar (1996), who found better model efficiency for Sy than for  $Q$  in rainfed corn of Chiapas, Mexico.

#### 4.4. Soil loss responses to variable steepness and residue cover

Because the interest in identifying appropriate components of no-till technology for alternative agricultural systems, it was necessary to assess the effect of crop residue coverage on sediment yield for a range of increasing hillslope steepness.

An assessment of soil loss responses for variable slope and residue cover was possible with GLEAMS after calibration. A no-till rainfed corn system with 3, 9, 15 and 25% hillslope steepness with 0, 20, 40, 60,

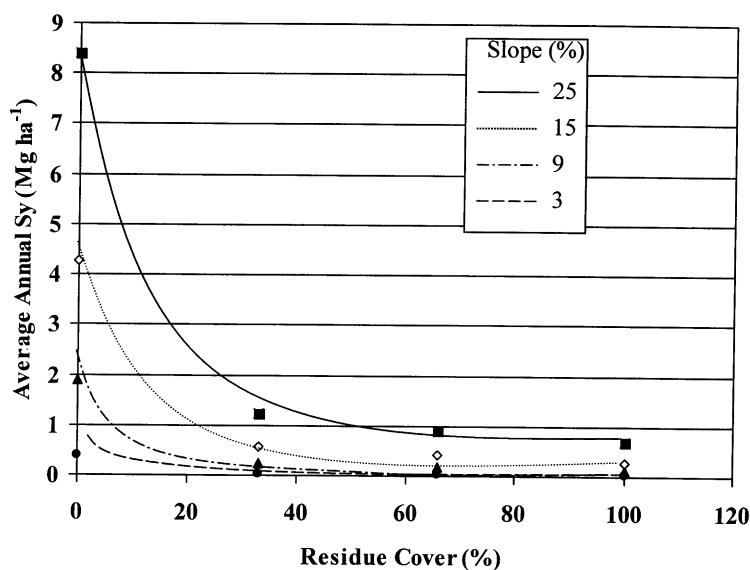


Fig. 4. Simulated sediment yield responses of no-till and residue soil cover treatments.

80 and 100% residue cover was simulated. Average sediment yield was obtained by running the model with observed climate data from year 1979 to 1996. Model results in Fig. 4 illustrate that  $S_y$  increased exponentially by reducing residue cover and increasing hillslope steepness. This indicates the existence of threshold values for residue cover as a function of

topography when a tolerable rate of soil losses is desired. For example, to keep sediment yield at  $1.0 \text{ Mg ha}^{-1} \text{ yr}^{-1}$  it is necessary to have 3, 8, 25, and 55% of residue cover for 3, 9, 15 and 25% slopes, respectively.

Soil losses at variable slope for the CT and NT systems were also compared (Fig. 5). An exponential

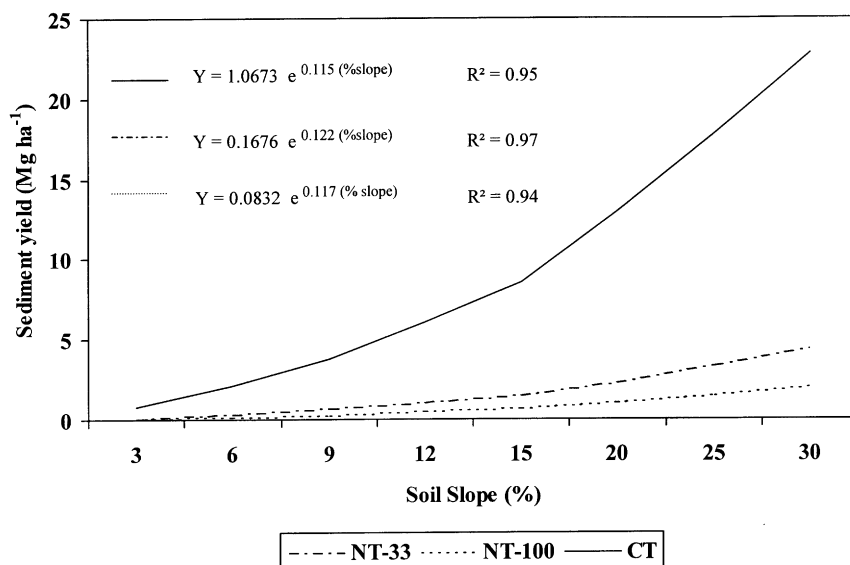


Fig. 5. GLEAMS sediment yield estimates for different hillslope steepness in the watershed.



fit of Sy rates against slope steepness was identified. CT soil loss at 4% soil slope was 1.2 and 23 Mg ha<sup>-1</sup> at 20% slope. NT with residue cover represents a viable solution to hillslope erosion in Patzcuaro basin, but soil losses were significant even in the NT-100 treatment when 25% slopes were cropped. Thus, the model became a tool to locate points along the hillslope where soil conservation structures (e.g. terracing) need to be installed to minimize soil losses.

Cropping the steep hillslopes of Patzcuaro Watershed has been the main cause of local soil and water resources depletion. Construction of soil conservation structures, like check dams, to reclaim the lake became a temporary solution to the problem. Deforestation and human activity can hardly be expected to end (Chacón, 1993), but no-till agriculture can be used to reduce the sediment loads and pollutants coming from agricultural uplands in this watershed, on which corn has been grown for more than 3500 years (O'Hara et al., 1993).

## 5. Conclusions

The modeling effort described here allowed us to quantify the potential impacts of no-tillage agriculture in reducing sediment outputs from agricultural hillslopes in comparison to current tillage system.

GLEAMS was able to adequately predict runoff and sediment yields from cultivated fields for a range of slopes. However, responses for sediment yield were much better than for runoff outputs. For the calibration stage the model efficiency index (*E*) ranged from 0.67 to 0.97 for runoff and from 0.95 to 0.96 for sediment yield, indicating the advantage of GLEAMS estimates in assessing the seasonal sediment yield over the observed mean of seasonal sediment. Thus the GLEAMS model represents an effective tool for the implementation of best management practices in steep slope agriculture. In the studied watershed, conventionally tilled agricultural fields are the major sources of sediment diminishing the lake water storage capacity. Fortunately, the amount of sediment dropping away from croplands can be reduced with conservation tillage. Nevertheless, further research is needed to document the effectiveness of alternative soil management along with the use of more extensive hydrological records for the simulation-modeling scheme.

Also, research is needed to monitor change in soil surface structure in NT treatments, and change in runoff over time.

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